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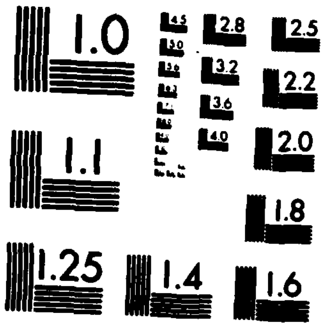
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by

Tuncay AKAL and Finn B. JENSEN

15 NOVEMBER 1983

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This memorandum has been prepared within the SACLANTCEN Underwater Research Division as part of Projects 05 and 19.

O.F. HASTRUP
Division Chief

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EFFECTS OF THE SEA-BED ON ACOUSTIC PROPAGATION

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Tuncay Akal and Finn B. Jensen

ABSTRACT

The sea-bed is known to be the controlling factor in low-frequency shallow-water acoustics. In lossy sea-beds waterborne sound is attenuated both by compressional-wave attenuation in the bottom and by the coupling of sound into shear waves. The complicated frequency-dependent effect of the sea-bed on propagation has been studied theoretically, and it is found that bottom loss increases with decreasing frequency down to near the cut-off frequency of the ocean waveguide, at which frequency seismic propagation by interface waves on the sea floor becomes more important than acoustic propagation. It is also found that while propagation losses in the water column are strongly dependent on bottom type, a feature such as the optimum frequency of acoustic propagation in the water column is only slightly dependent on sea-bed properties. Broadband propagation data collected in different areas of the Mediterranean Sea and the eastern North Atlantic are shown to support these theoretical findings.

1 INTRODUCTION

Acoustic propagation in the ocean is influenced by many factors: physical and chemical properties of sea water cause attenuation and refraction, while different types of sediments, layering, and rough surfaces complicate reflection.

The frequency range of ocean acoustics extends roughly from a few hertz to several hundred kilohertz. This means that acoustic signals propagating in the ocean with the speed of sound will have acoustic wavelengths extending from 1500 m down to 5 mm, a range of almost six orders of magnitude. With long-range propagation (hundreds of kilometres) the higher frequencies are attenuated, so that the useful frequencies are limited to a range from a few hertz to only a few kilohertz. Acoustic energy propagates into and out of the sea-bed and is scattered from the sea surface; however, varations of sound speed with depth control the influence that these boundaries have on the propagation. Thus the boundaries (sea surface and sea floor) and the physical and acoustical properties of the sea-bed become essential factors in acoustic transmission through the ocean.

To illustrate the effects of the sea-bed on acoustic propagation we have selected a characteristic example from our experimental broadband acoustic data files, which contain hundreds of acoustic propagation runs from the northern and eastern North Atlantic and the Mediterranean sea. Figure 1 is an example of the results of an experiment designed to measure transmission loss in the ocean [1]. Since transmission loss is a function of both frequency and range, a simple way of displaying all significant information is to use isoloss contours in a frequency/range plane, as shown in the upper plot of the figure. The classical propagation-loss versus range curves can be retrieved from this type of plot by making a horizontal cut at the frequency of interest. The transmission losses displayed in Fig. 1 were measured over an acoustic path extending from deep to shallow water; the receiver (60 m) was situated in deep water while the source (50 m) moved from deep water to shallower water on the continental shelf. For ranges less than 50 km, the propagation was characteristically of the deep-water type: the lower the frequency, the better the propagation. When the source moved over the continental shelf, at a range of approximately 70 km from the receiver, the propagation characteristics changed drastically. Because low-frequency sound (< 100 Hz) interacts more with the sea-bed it is severely attenuated, thereby creating an optimum frequency of propagation at around 126 Hz in this experiment. This example clearly illustrates the effects of the sea-bed on propagation.

2 PARAMETERS THAT CONTROL ACOUSTIC INTERACTION WITH THE SEA-BED

While propagating through the ocean, acoustic energy is prevented from spreading beyond this medium and remains mostly confined between the sea surface and the bottom. However, the degree of interaction of the acoustic energy with the sea-bed is not constant but is determined mostly by the sound-speed structure and the thickness of the water column.

When the sound-speed profile has a negative gradient from the sea surface to the bottom (summer conditions), acoustic energy is refracted towards the bottom, so that acoustic propagation becomes particularly dependent on the bottom configuration and on the properties of the bottom and sub-bottom sediments. When, on the other hand, the sound-speed profile has a positive gradient (winter conditions) the upward-refraction conditions reduce the influence of the sea-floor. These effects are evident in the results of two acoustic runs made over the same propagation path under summer and winter conditions (Fig. 2). It is clearly seen that losses are much higher in summer than in winter conditions.

Water depth is the other important parameter in the interaction of acoustic energy with the sea-bed. The thickness of the propagation channel, defined by the surface and bottom, controls the number of interactions of the sound rays with the sea bottom. When the water is shallow, acoustic energy interacts more with the bottom and hence is subject to higher losses. Figure 3 shows the effect of water depth on propagation by comparing transmission losses in the same area under the same environmental conditions but at different water depths. As can be seen, the greater the water depth, the smaller the losses and the lower the optimum frequency. This is because, at all frequencies, bottom interaction decreases with increasing water depth. The effect of changing water depth on the optimum frequency of propagation is also evident in Fig. 1.

Another important phenomenon is also controlled by the thickness of the propagation channel, i.e., by the water depth. Wave theory predicts that for any kind of ducted propagation there is a cut-off frequency below which the duct ceases to act as a waveguide. This cut-off frequency is inversely proportional to the water depth, being around 10 Hz in 100 m of water. Below the cut-off frequency, water-borne acoustic propagation is extremely poor, and seismic interface waves then become important propagation paths.

3 EFFECT OF BOTTOM TYPE ON PROPAGATION

When waterborne sound interacts with the sea-bed, some energy is transferred from the water column to the bottom. The fractional energy transfer depends on the lossiness of the bottom, which, in turn, is determined by the acoustic properties of the bottom material.

For visco-elastic bottoms the acoustic properties are completely defined by the compressional and shear-wave velocities, the attenuation factors associated with these waves, and the material density. (More complex bottoms, such as those described by poro-elastic Biot models [2] will not be dealt with in this paper). In simple bottom models based on visco-elastic theory, shear properties are often neglected, which can be justified only for very 'soft' sediments (clay-silt), in which shear speeds are low (< 200 m/s). In harder, unconsolidated sediments, shear properties are very important and, in some cases, even dominate the reflection properties. Moreover, the existence of interface waves on the sea floor is intrinsically related to the shear properties of the bottom material.

To demonstrate the effect of shear in the bottom on acoustic propagation in the water column, we turn to a set of experimental data collected in shallow water in the Mediterranean. The measured sound-speed profile is shown in Fig. 4, together with the source (50 m) and receiver (40 m) positions. The water depth is 70 m and the downward-refracting profile causes strong sound interaction with the sea floor. Hence, we can expect long-range (tens of kilometres) propagation in this area to be strongly affected by bottom loss.

The bottom properties used for numerical modelling of this propagation condition are listed on Fig. 4. The bottom material is primarily sand, with density and compressional speed (C_c) determined directly from bottom cores taken in the area. The other parameters — shear speed (C_s), compressional-wave attenuation (β_c), and shear-wave attenuation (β_s) — were determined so as to give the best agreement between computed and measured propagation losses. Parameter values estimated in this manner were checked against values reported in the literature for similar bottom types, and all the parameter values given are well within the range of values reported by Hamilton [3] for sand bottoms.

Figure 5 shows the measured propagation loss at a range of 30 km as a function of frequency. Note that best propagation (optimum frequency) occurs between 200 and 400 Hz. The figure also presents two theoretical curves that have been computed by a fast-field program (FFP) capable of providing an exact numerical integration of the wave equation for a horizontally stratified environment; this program was developed originally by Kutschale [4] and modified recently by Schmidt [5]. Two theoretical curves are shown: one neglecting shear properties in the bottom, and one including shear waves with a speed of 500 m/s. We see that shear is an important loss mechanism at all frequencies (10 dB at 3.2 kHz), even though shear losses are highest at low frequencies (35 dB at 50 Hz). In fact, shear losses move the apparent cut-off frequency up from around 15 Hz to around 40 Hz. Note that shear effects are particularly evident below the optimum frequency of propagation. Considering the above example and several more reported in [6], it is seen that shear rigidity is clearly a fundamental property of ocean-bottom materials and must therefore be included in a realistic model of the sea-bed.

To assess the general frequency-dependent propagation characteristics in water overlying different bottom materials, the same FFP model [4, 5] was used to make a parametric study. Four different bottom types were investigated, as shown in Table 1. Realistic estimates of the geoacoustic parameters were obtained from [3]. Note that shear properties are specified for all bottom types. Even though there is some uncertainty associated with the numerical values given in Table 1, particularly concerning the shear properties, we feel that these values are sufficiently representative of real ocean bottoms to be useful in making a meaningful study of bottom effects on propagation.

TABLE 1

GEOACOUSTIC PARAMETERS FOR DIFFERENT BOTTOM TYPES

Bottom Type	Density (g/cm^3)	Compress. speed (m/s)	Shear speed (m/s)	Compress. attenuation (dB/λ)	Shear attenuation (dB/λ)
SILT	1.8	1600	200	1.0	2.0
SAND	2.0	1800	600	0.7	1.5
LIMESTONE	2.2	2250	1000	0.4	1.0
BASALT	2.6	5250	2500	0.2	0.5

We consider propagation in the simplified environment summarized in the upper left corner of Fig. 6; i.e., 100 m of isovelocity (1500 m/s) water overlying a homogeneous bottom. The source is placed at mid-depth (50 m) and the receiver on the bottom (100 m). Propagation-losses over a range of 10 km were calculated for the four bottom types for a wide spectrum of frequencies (0.1 Hz to 1 kHz), as shown in the four curves of Fig. 6.

The general frequency-dependent propagation characteristics of the water channel are well illustrated by the result shown for a homogeneous silt bottom. Above 40 Hz (optimum frequency) there is good propagation with an apparent cut-off of water-borne sound when the frequency falls below about 10 Hz. At very low frequencies (0.1 to 0.3 Hz) seismic propagation becomes important, and sound propagates as an interface wave along the sea floor. This wave type has the highest excitation on the water/bottom interface and an exponentially decaying amplitude away from the interface. The seismic interface waves have been shown to exist in many ocean areas [7], and since this wave type is intrinsically related to the shear properties of the bottom, the experimental evidence of the existence of these waves is yet another proof of the importance of shear effects in low-frequency ocean acoustics.

The general broadband propagation characteristics found with a silt bottom are also evident with the other three bottom types, though with different transmission-loss levels. We note that the interface-wave excitation increases with the shear speed (lowest for silt, highest for limestone), and that the excitation peak moves to higher frequencies for higher shear speeds. The interface wave becomes an integral part of the water-borne spectrum when the shear speed is higher than the water speed, which is the case for basalt. Seismic interface waves are seen to be an important propagation path only below 5 Hz, and because of the quite high attenuation of these waves, maximum useful detection ranges seem to be of the order of 10 km. A detailed theoretical study of the excitation and propagation of interface waves for realistic layered bottoms has been done by Schmidt [5].

Returning to water-borne propagation (above 5 Hz), we see from Fig. 6 that the best propagation is associated with a basalt bottom, while limestone is the most absorptive bottom of those investigated here. This is somewhat surprising considering the fact that limestone is a compact material with high density and high compressional speed. Its shear speed, however, is very close to the water speed, causing strong coupling of water-borne sound into shear waves in the bottom. The relative lossiness of the four bottom types is also clearly seen from the plane-wave reflection curves presented in Fig. 7, which have been computed from a numerical model developed by Hastrup [8]. Since good propagation is associated with small grazing angles (< 20°), we would expect to have the best propagation over a basalt bottom, followed by those of silt, sand, and limestone.

The concept of an optimum frequency of propagation has been addressed earlier, and can be shown to be a fundamental property of long-range propagation in the ocean. A detailed study has been done by Jensen and Kuperman [9] to investigate the effect of various environmental factors on the optimum frequency. In short, it was found that the optimum propagation frequency is strongly dependent on the water depth, somewhat dependent on the sound-speed profile, and only weakly dependent on the bottom type. This is a surprising conclusion considering that the level of propagation loss is strongly dependent on the bottom properties.

Final experimental evidence of the effects of the sea bottom on propagation is given in Fig. 8, which presents measured transmission losses from different areas of the Mediterranean and the eastern North Atlantic. Water depths were in all cases around 100 m, with source and receiver around mid-depth. Sound-speed profiles were of summer type, and the selected areas all represent different bottom types. The measured losses at 30 km range are seen to vary by approximately 10 dB above the optimum frequency (200 to 400 Hz), while much greater transmission-loss differences are recorded at low frequencies. Figure 8 provides further confirmation that the sea-bed is of paramount importance to low-frequency ocean acoustics.

SUMMARY AND CONCLUSIONS

The sea-bed is the controlling factor in low-frequency acoustic propagation in the ocean. We have seen clear evidence of the importance of shear, both as a loss mechanism for waterborne sound, and as a propagation mechanism for seismic interface waves. The interface waves will be important only at short range (< 10 km) and at very low frequencies (< 5 Hz). Waterborne sound is subject to bottom-reflection loss, particularly at low frequencies, causing a shift of the apparent cut-off to higher frequencies. Moreover, the lowest propagation loss is found for bottoms with both low and high shear speeds, while high propagation losses occur for bottoms with intermediate shear speeds, of the order of the water speed.

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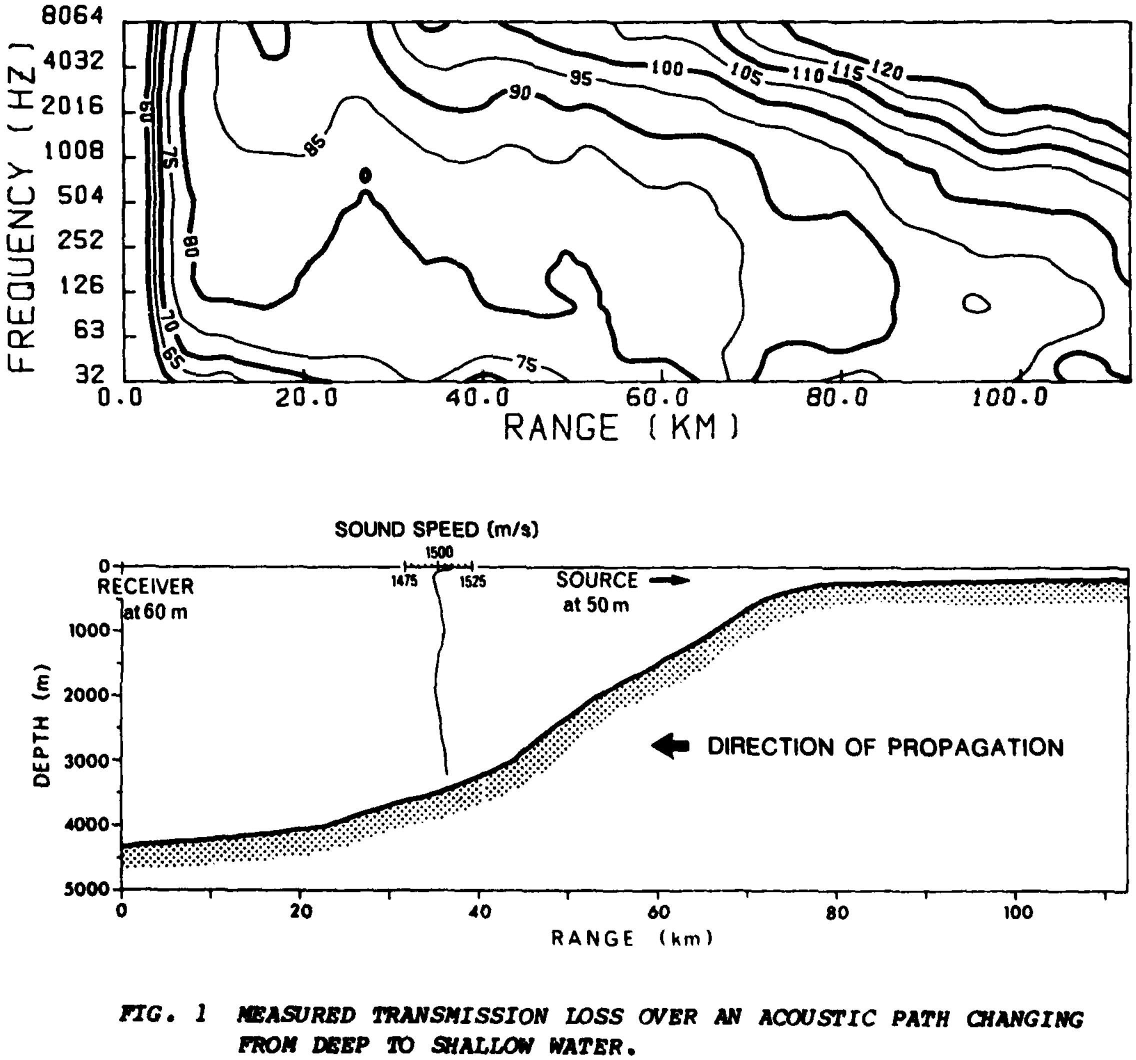

FIG. 1 MEASURED TRANSMISSION LOSS OVER AN ACOUSTIC PATH CHANGING FROM DEEP TO SHALLOW WATER.

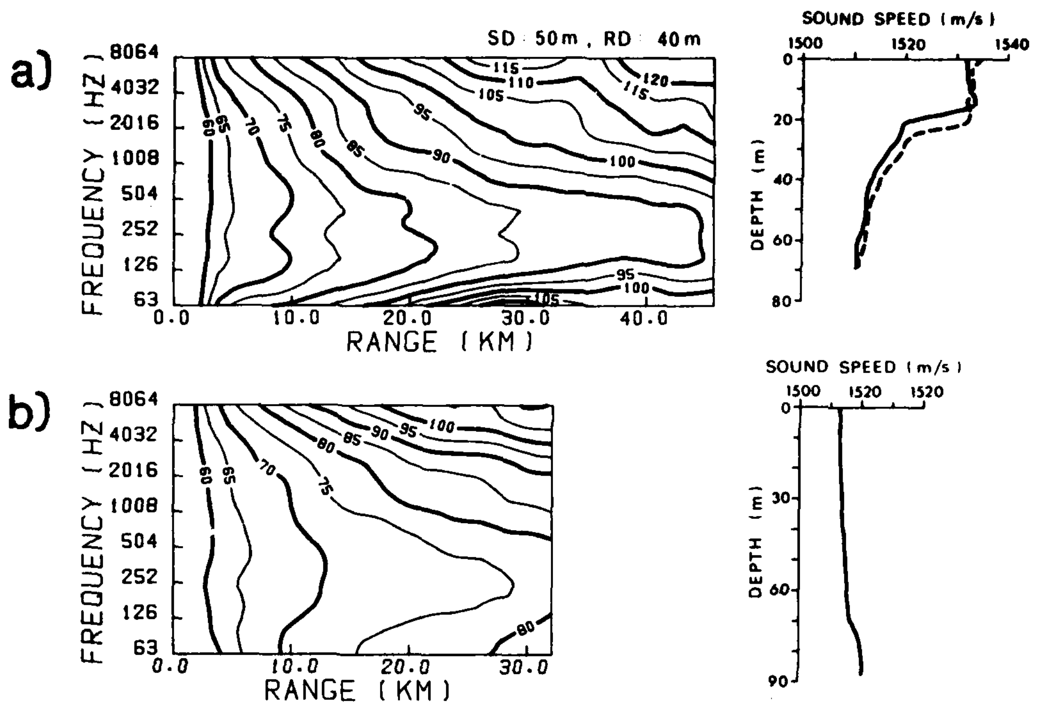

FIG. 2 TRANSMISSION LOSSES MEASURED OVER THE SAME PROPAGATION PATH.
(a) Summer conditions
(b) Winter conditions

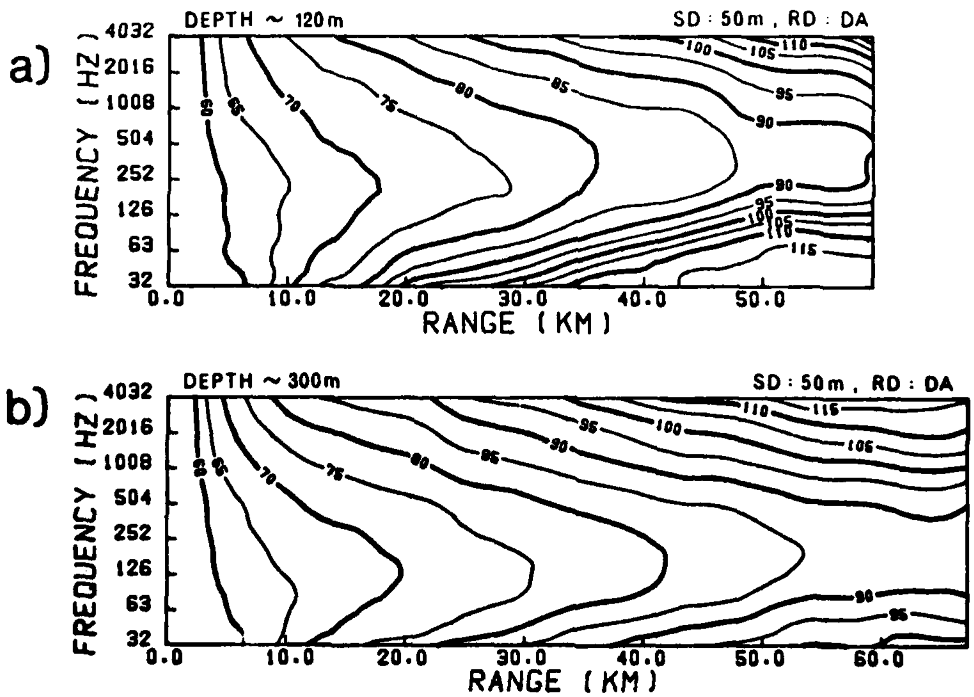

FIG. 3 EXPERIMENTAL EVIDENCE OF THE EFFECT OF WATER DEPTH ON PROPAGATION.
(a) 120 m water depth
(b) 300 m water depth

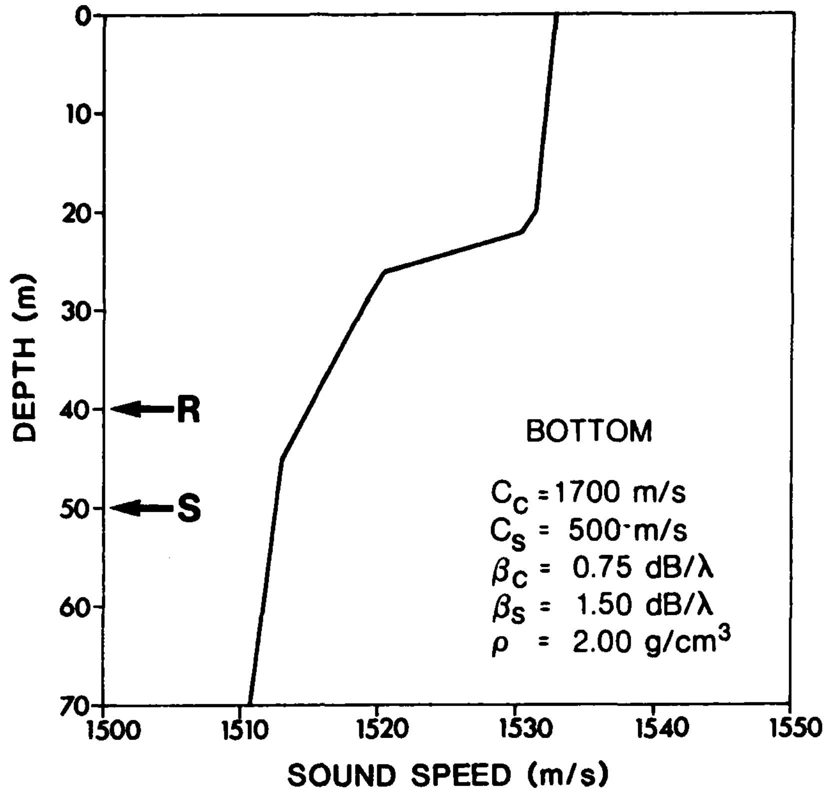

FIG. 4 SOUND-SPEED PROFILE AND BOTTOM PARAMETERS FOR SHALLOW-WATER AREA IN SOUTHERN MEDITERRANEAN.

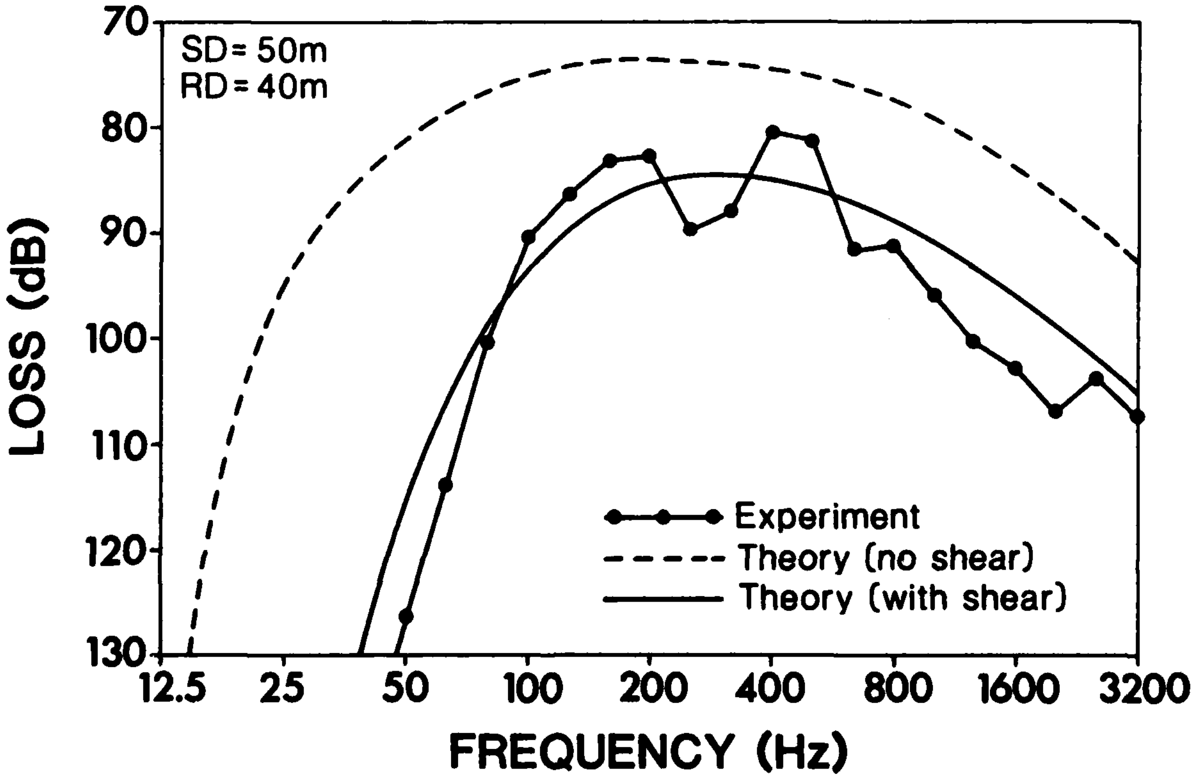

FIG. 5 MEASURED AND COMPUTED PROPAGATION LOSSES AT RANGE 30 km.

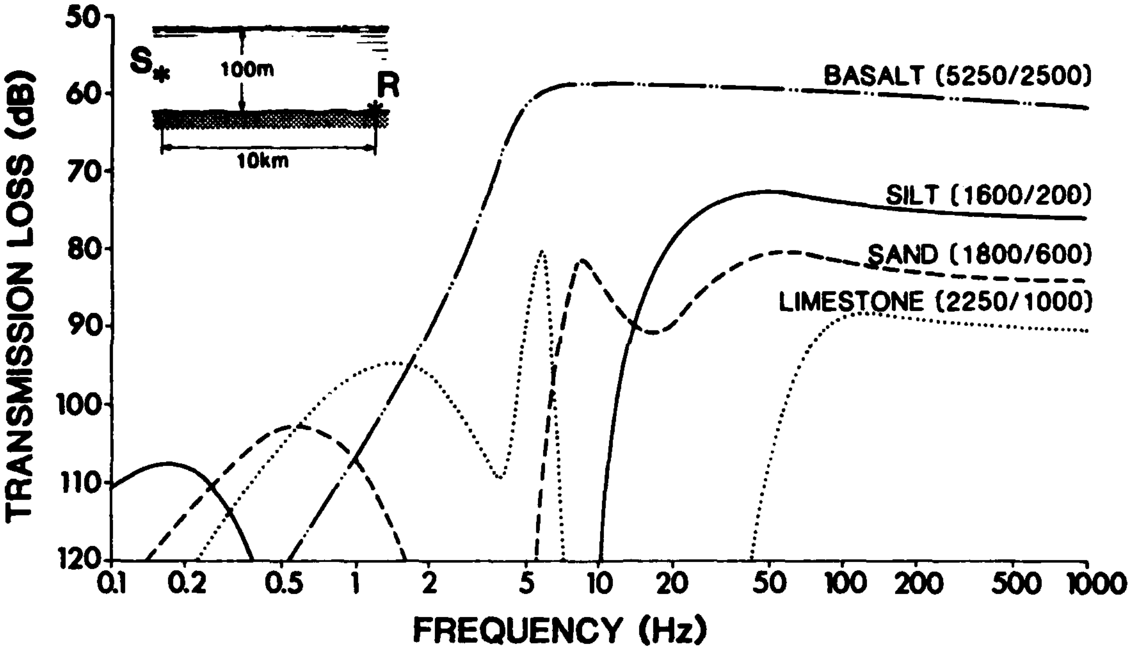

FIG. 6 BROADBAND PROPAGATION CHARACTERISTICS FOR DIFFERENT BOTTOM TYPES. Numbers in parentheses are compressional and shear speeds, respectively.

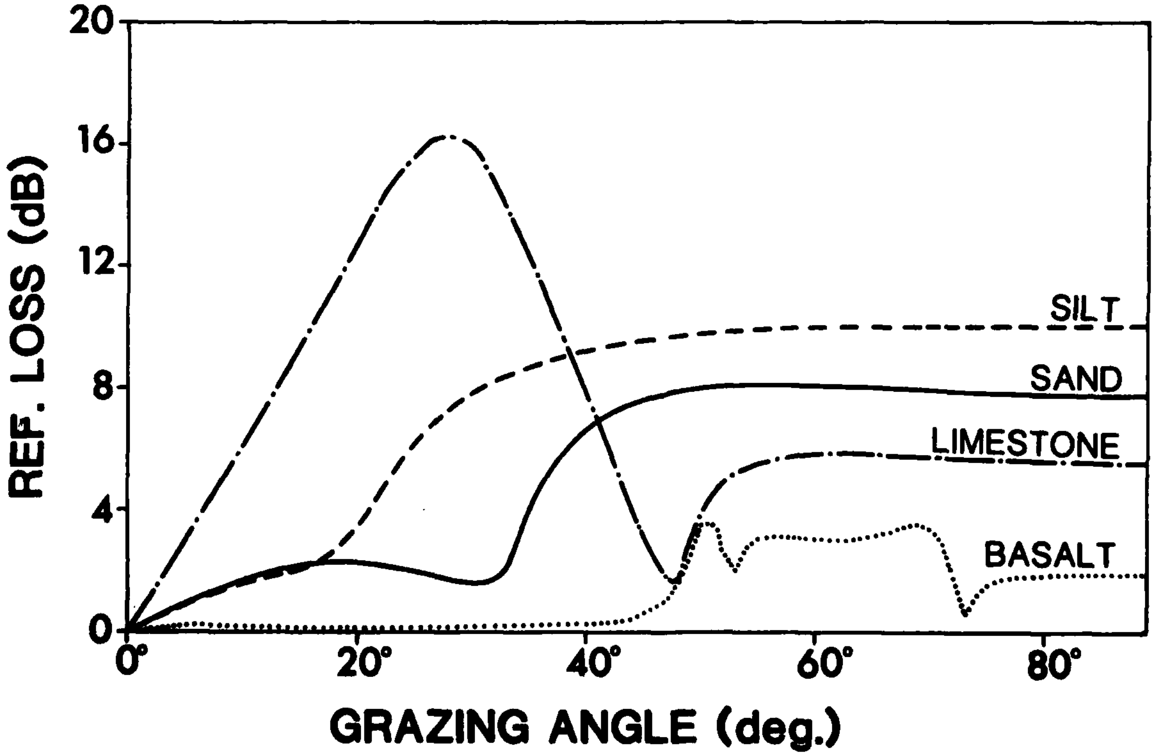

FIG. 7 COMPUTED REFLECTION LOSS vs GRAZING ANGLE FOR DIFFERENT BOTTOM TYPES.

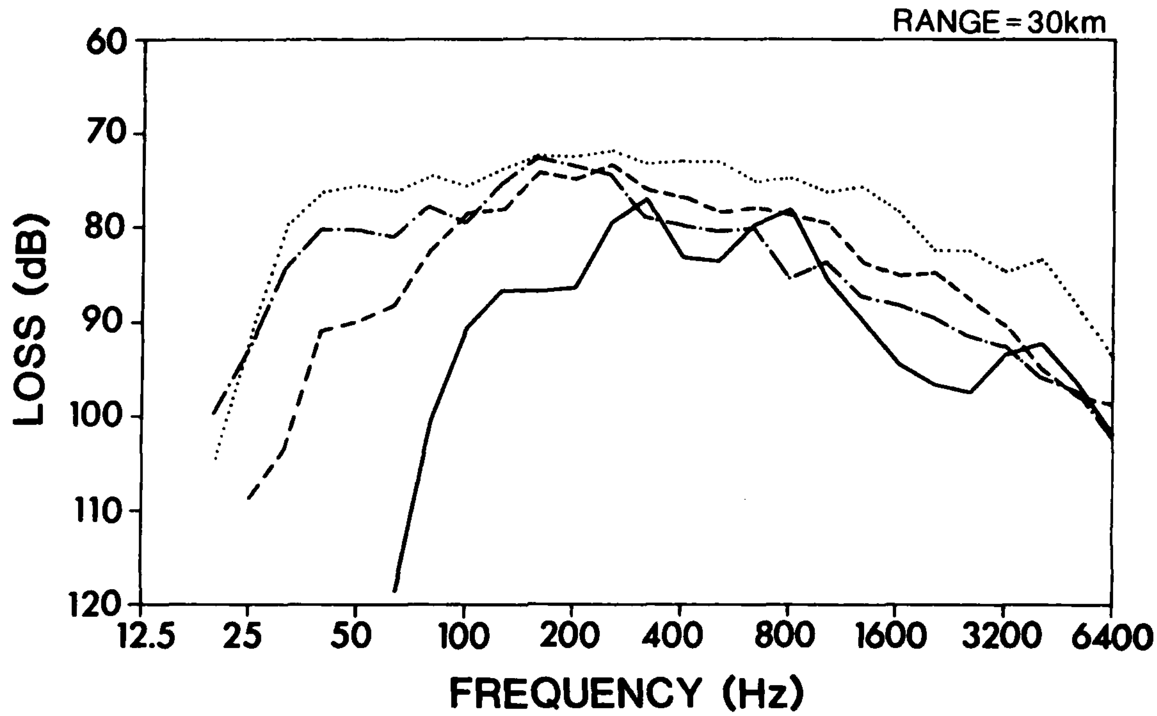

FIG. 8 MEASURED PROPAGATION LOSSES IN DIFFERENT OCEAN AREAS.

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